UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

# SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

# REACTOR VESSEL WELD FLAW EVALUATION

# TENNESSEE VALLEY AUTHORITY

# BROWNS FERRY NUCLEAR PLANT UNIT 3

# DOCKET NO. 50-296

## 1.0 Introduction

By letter dated March 6, 1995, the Tennessee Valley Authority (the licensee) submitted the results of an augmented inservice inspection of the reactor vessel shell welds at the Browns Ferry Nuclear Plant (BFN) Unit 3. After a preliminary review of this submittal, the staff requested the licensee to submit additional information regarding flaw evaluations of those indications that exceeded the acceptance criteria of IWB-3500 of Section XI of the ASME Code. By letters dated October 4, October 9, and November 7, 1995, the licensee submitted flaw evaluations for staff review. The licensee concludes that the flaws will not exceed the allowable flaw sizes for at least 12 Effective Full Power Years (EFPY).

NRC regulations 10 CFR 50.55a(g)(6)(ii)(A) and 10 CFR 50.55a(g)(6)(ii)(A)(2) require an augmented examination of reactor pressure vessel (RPV) shell welds. In accordance with 10 CFR 50.55a(g)(6)(ii)(A)(2), the extent of the examination for the RPV welds was determined from the 1989 Edition of the American Society of Mechanical Engineers (ASME) Section XI for examination category B-A, Item number B1.10. The licensee used examination techniques and evaluation criteria in accordance with the 1986 Edition of the ASME Code Section XI, the BFN Unit 3 code of record (1974 Edition, Summer 1975 addenda), and Regulatory Guide (RG) 1.150.

IWB-3132.4(a) of Section XI of the ASME Code states that components whose volumetric or surface examination reveals flaws that exceed the acceptance standards listed in Table IWB-3410-1 shall be acceptable for service without flaw removal, repair, or replacement if an analytical evaluation, as described in IWB-3600, meets the acceptance criteria of IWB-3600. Table IWB-3410-1 refers to acceptance standards in IWB-3500 for the specific component and part that are examined. Flaws detected during inservice inspection must satisfy the requirements of IWB-3500 to justify continued operation. IWB-3134 states:

> Analytical evaluation of examination results as required by IWB-3132.4 shall be submitted to the regulatory authority having jurisdiction at the plant site.

ENCLOSURE

In addition, IWB-3132.4 states:

> Where the acceptance criteria of IWB-3600 are satisfied, the area containing the flaw shall be subsequently reexamined in accordance with IWB-2420(b) and (c).

In addition to the above ASME Code evaluation, the licensee conducted a "Spirit of Appendix VIII" performance demonstration inspection to evaluate the adequacy of procedures, personnel, and equipment. The performance demonstration inspection was modeled in accordance with Appendix VIII to Section XI of the ASME Code, 1989 Edition.

## 2.0 Evaluation

The RPV at BFN Unit 3 was fabricated by Babcock and Wilcox and Ishikawajima-Harima Heavy Industries. The RPV has a wall thickness of 6.125 inches at the beltline and a nominal 0.188 (3/16) inch thickness for the cladding at the inside surface of the vessel and bottom head. There is no clad within the top head or head flange regions.

The licensee contracted General Electric (GE) to perform the RPV shell welds augmented examination at BFN Unit 3 during the cycle 5 extended outage. The examination was completed in late 1993. The examination was conducted with the GE Remote Inspection System 2000 ultrasonic equipment. The examination was complemented with a manual examination of selected areas from the outside of the RPV to maximize the percentage of weld volume examined. GE examined a total of five circumferential shell welds and 15 longitudinal shell welds.

The results of the augmented ultrasonic (UT) examination showed that of all RPV welds inspected, four RPV shell welds had a total of ten indications that exceeded the allowable standards of ASME Code Section XI, IWB-3500. The indications were located in welds C-2-3, C-3-4, C-4-5, and V-4-B. One indication was recorded in both welds V-4-B and C-3-4 due to their intersecting weld joints. The indications were located in the vessel flange welds and non-beltline region welds. The non-beltline welds are the circumferential welds between the upper shell course and the intermediate shell course; and between the upper shell course and nozzle shell course. Indication 12-116 has the largest UT measured depth, 2a, of 0.62 inch of the ten indications; its measured length is 0.75 inch. Indication 12-148 has the longest measured length of 2.75 inches; its measured depth is 0.511 inch. These two indications were found in the non-beltline circumferential welds.

The licensee characterized all ten indications as subsurface flaws and as embedded volumetric anomalies caused by fabrication. They were not previously detected with ultrasonic examinations at the time of fabrication. The licensee stated that numerous similar indications were present that were either of acceptable size or have no target motion (walking indication as identified in RG 1.150). In addition to the welds inspected as part of the augmented examination, another weld (C-5-FLG, ASME Code category B-A, Item No. B1.30) was inspected and contained five indication which exceeded IWB-3500. These indications were evaluated along with indications discovered by the augmented examination.

For those indications that exceeded IWB-3500, the licensee performed a flaw evaluation in accordance with IWB-3600 (1986 Edition) acceptance criteria. The licensee's flaw evaluation was based on comparing the indications to the allowable flaw size that were developed in the bounding analysis, "Vessel Flaw Evaluation for Browns Ferry Nuclear Plant Unit 3," the licensee calculation No. MD-Q3001-920553, which was performed by GE.

The bounding analysis was based on the linear elastic fracture mechanics calculation in Appendices A and G to Section XI of the ASME Code. The analysis developed the allowable flaw size for an irradiation level and fatigue crack growth corresponding to 12 EFPY. The RPV axial and circumferential welds were grouped in terms of regions - top head, head flange, vessel flange, non-beltline region, beltline region, and bottom head.

The following loadings were considered in the calculations of the allowable flaw size: clad residual stress, weld residual bending stresses, membrane pressure stresses, and flange boltup stresses. These stresses were applied to the welds depending on the regions in the RPV where the welds would experience such loads. For example, beltline region welds would not have bolt preload stress applied to them because they are outside of the boltup stress influence. The licensee stated that thermal stresses due to normal operating conditions, such as heatup and cooldown, need not be considered because the isothermal hydrostatic test and boltup conditions are more limiting (i.e., having lower allowable fracture toughness) than any other conditions.

The clad stress is caused by the cooling of the vessel below the post-weld heat treatment to relieve the residual stresses after the clad is welded to the vessel shell plate. GE stated that at a hydrotest temperature of 185°F the residual clad stress is about 24 kilopounds per square inch (ksi), and 28 ksi at 144°F in bottom head regions due to thermal expansion.

The boltup stress is caused by the tightening of the vessel head bolts. The preload in the bolt is balanced by the reaction force in the gasket. These opposing forces generate a moment on the flange which induced compressive stresses on the inside surface near the flange welds. However, this stress decreases with distance and becomes negligible at a short distance from the flange. Therefore, only the vessel flange and head flange welds are affected by bolt preload stresses. Membrane and bending stresses for the flange weld locations were based upon typical stress results at flange discontinuities for a 251-inch vessel such as the BFN Unit 3 RPV. GE performed a finite element analysis to characterize the attenuation of bending stresses with distance away from the flange discontinuities. Based upon the location of the welds, appropriate stress attenuation coefficients were applied to the discontinuity stresses to determine the bending stresses at the flange welds.

The pressure stress is caused by the pressurization of the vessel. For axial flaws, the hoop stress was calculated for a thin-walled pressure vessel, PR/t, where R is the inside vessel radius, P is the pressure, and t is the vessel thickness. The limiting load applied was at the hydrotest condition of 1100 pounds per square inch, gage (psig) pressure and a temperature of 185°F, which was obtained from the pressure-temperature limits at 12 EFPY in the BFN

Unit 3 Technical Specifications. For circumferential flaws, the axial stress was calculated using PR/2t.

The weld residual stress is caused by the seam weld or the flange weld and is reduced as a result of post-weld heat treatment. However, some weld residual stress still remains after the heat treatment. Based on previous analysis for seam welds, GE used 8 ksi in both axial and circumferential directions for flaws oriented parallel to the weld line. For flaws oriented perpendicular to the weld line, the weld residual stress is zero.

The above stresses were used to develop the applied stress intensity factor, $K_I$, as a function of the flaw depth ratio, a/t, for surface flaw or a/2t for subsurface flaw and aspect ratio, a/L. The allowable stress intensity factor, $K_{allow}$, was developed from the material fracture toughness, $K_{IA}$, which was calculated based on Appendix G to Section XI of the ASME Code. For each weld location, $K_{IA}$ was determined based on either limiting reference temperature for nil-ductile transition ($RT_{NDT}$) values, if the weld is not affected by radiation embrittlement, or adjusted reference temperature (ART) as calculated by Regulatory Guide 1.99, Revision 2, if the weld is affected by radiation embrittlement. The licensee considered the loadings for normal operation, emergency, and faulted conditions in its analysis. The $K_{allow}$ was limited to $K_{IA}/\sqrt{10}$ for normal conditions and $K_{IA}/\sqrt{2}$ for emergency and faulted conditions as specified by IWB-3612. Equating $K_I$ to $K_{allow}$, a series of allowable surface flaws and subsurface flaws were solved and were constructed for RPV welds. The licensee demonstrated that the hydrostatic test and boltup conditions provided the most limiting condition. The reason is that the reactor vessel temperature during hydrostatic test conditions is low as compared to emergency and faulted transients, thus resulting in a lower allowable fracture toughness. Additionally, the required factors of safety are lower for the emergency and faulted conditions than normal conditions.

The fatigue crack growth was based on equations in Article A-4300 of Appendix A to ASME Section XI. For inside surface flaws, the fatigue crack growth equation was based on a water environment. For the outside surface flaws and subsurface flaws, the fatigue crack growth equation was based on an air environment. GE assumed the maximum difference in $K_I$ to obtain a conservative crack growth. At the time of the bounding analysis in 1992, BFN Unit 3 had reached 6 EFPY of operation. Since the bounding analysis was limited to 12 EFPY, the crack was calculated for 6 EFPY of growth. The maximum fatigue crack growth was found to be 0.055 inch for a period of 6 EFPY. The fatigue crack growth allowances were used to adjust the limiting flaw sizes obtained from fracture mechanics calculation to develop the allowable flaw size.

The upper bound of the allowable flaw size was established by ASME Section III requirements for primary local stress which states that the maximum primary membrane stress cannot exceed $1.5S_m$. GE limited the surface and subsurface flaws to be within 1/3 of the thickness of the base metal. For the inside surface flaw, the 1/3 limit is conservatively measured from the surface of the clad, and not from the clad/base metal interface. The lower bound of the allowable flaw size was established by the acceptance criteria of IWB-3500. The allowable flaw sizes per IWB-3600 are between the upper and lower bounds.

The staff determined that the bounding analysis is acceptable because it was developed in accordance with Sections III and XI of the ASME Code. The staff confirmed that the indications are within the allowable flaw sizes that were developed for 12 EFPY. As required by IWB-3132.4(b), the licensee is required to reexamine the indications in the next three inspection periods. In addition, the licensee is required to submit an analysis to justify continued operation beyond 12 EFPY because the indications were dispositioned for 12 EFPY.

## 3.0 CONCLUSION

1. The licensee has demonstrated that indications that exceed IWB-3500 of Section XI of the ASME Code are within the IWB-3600 acceptance criteria.

2. The licensee has demonstrated that the Brown Ferry Unit 3 plant is acceptable for continued operation up to at least 12 EFPY because the indications will not grow to exceed the allowable flaw sizes that are calculated for 12 EFPY.

3. The licensee is required to submit an analysis to justify continued operation beyond 12 EFPY considering the existence of the indications.

4. In accordance with IWB-3132.4(b) of Section XI of the ASME Code, the licensee is required to reexamine the indications in the next three inspection periods in accordance with IWB-2420(b).

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BROWNS FERRY NUCLEAR PLANT

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